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PRESSURE WAVE MEASUREMENTS DURING THERMAL EXPLOSION OF HMX-BASED HIGH EXPLOSIVES*

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Five different experiments on thermal heating of explosive materials have been performed. Three experiments thermally exploded PBX 9501 (HMX/Estane/BDNPA-F; 95/2.5/2.5 wt %) donor charges while two others thermally exploded LX-04 (HMX/Viton A; 85/15 wt %). These donor charges were encased in 304 stainless steel. The transmitted two-dimensional pressure waves were measured by gauges in acceptor cylinders of Teflon, PBX 9501, or LX-04 that were in contact with the donors' steel case. A fifth experiment measured the pressure in an acceptor charge of PBX 9501 that had a 100 mm stand-off from the top of the steel case of the thermally cooked off PBX 9501 donor charge. Reactive flow hydrodynamic modeling using a rapid deflagration velocity of approximately 500 m/s was able to reproduce the pressure gauge records for both the in contact and stand off experiments that used PBX 9501 donors and acceptors.

INTRODUCTION

A better understanding of thermal explosion is needed for safe handling, transportation, and storage of explosive devices. Questions exist on the level of violence of these events as a function of confinement and thermal heating rates. Experimental measurements of the violence of thermal explosion events of known sizes, confinements, and thermal histories are essential for developing and calibrating reactive flow computer models for calculating events that are impossible to measure experimentally. The measured acceleration of metal cases from thermal explosion is also needed to assess whether the resulting flying fragments can shock initiate violent reaction or detonation in a neighboring explosive item. The current experiments were heated at rate of 5.7 ° C until 170 ° C is reached then at a rate of 1° C per minute until reaction occurred. Another set of experiments[1] heated these same explosives at a rate of 1° C per hour. These different heating rates bound many of the safety scenarios of interest. The ability to model these two different experiments will provide confidence in predictions without requiring experimental validation in all circumstances. In this paper, for the first time, pressure gauge measurements are used to quantitatively determine the level of violence in a cook-off experiment. Carbon resistor pressure gauges are used to measure low-pressure ramp waves with pulse widths greater than 1.5 μs. Carbon resistor gauges have been successfully used in two-dimensional shock wave experiments where time resolution and accuracy were sacrificed for survival of the gauge.[2-6] The calibration of the carbon resistor gauge has been done by numerous researchers.[2,3,7,8]

EXPERIMENTAL PROCEDURES

Five different experiments thermally exploded steel confined PBX 9501 or LX-04 donor charges. The donor charge confinement assembly design has been kept constant for all

experiments. The PBX 9501 donor discs were isostatically pressed to 1.82 g/cc, and one LX-04 donor was isostatically pressed to 1.86 g/cc, while the other LX-04 donor (same lot as other) was hand packed to a density of 1.05 g/cc. The explosive acceptor discs were machined out of the same pressed billets as the donor charges. The assembled experiments were placed inside a large steel expendable cylinder to protect the firing chambers walls. The acceptors were in contact with the donor system's top steel plate for four of these experiments. Experiment TEXT VII had the acceptor stood off from the donor steel case top by 100 mm. This experiment was designed to see what kind of pressure would be induced from the impact of the steel case at its terminal velocity after acceleration by the cook-off event that occurred in the steel encased PBX 9501 donor.

The pressure ramp waves generated in all experiments were measured by carbon resistor pressure gauges placed in machined grooves in the acceptor at various locations. The resistor gauge is a standard 1/8 W, 470 Ω carbon composition resistor made by Allen-Bradley Corporation. It is a 1.6 mm diameter by 4 mm long cylindrical resistor. It has a peak pressure accuracy of ± 15% for pressures less than 4 GPa and a temporal resolution of 1.5 μs based on 4.5 wave transits through the resistor to reach equilibrium with host material's pressure state.

Manganin foil pressure gauges were also placed in the acceptors just in case the explosive reaction in the acceptor built to a detonation. Detonation pressures are typically 20-40 GPa, which is above the carbon resistor gauge operating range. Manganin foil gauges are well established for measurement of one-dimensional shock wave pressures[9-11] from 2.0 to 75 GPa and have also been shown to be temperature insensitive[9,12]. For this investigation, manganin records need corrections for large lateral strain[13] because the flow is multi-dimensional. The manganin gauge data is not presented here because all reactions created sub-detonation pressures in these experiments and the recording times for the manganin gauges were less than the measured pressure ramp waves rise-times.

The donor assembly was made up of a 12.4 mm thick 304 stainless steel top plate fastened to the 12.4 mm bottom 304 steel plate with several "grade-8" hardened steel bolts tightened to 95 N-m (70 ft-lbs). The 90 mm by

25 mm thick disk of explosive was radially constrained by a 304 stainless steel ring with wall thickness of 34.5 mm. The ring height and diameter were slightly greater than the explosive at room temperature to allow the explosive and metal container to come into contact when the explosive reaches 150 ° C. A 3 mm thick aluminum or copper plate was placed between the front steel plate and explosive to distribute the heat faster and more uniformly across the explosive/metal interface than would occur for just a steel plate. The aluminum or copper plate also served as a gasket for a pressure seal since both steel interfaces had knife edges machined in them. The flat nichrome spiral ribbon heater of outer diameter of 66 mm, width 2.5 mm and thickness 0.1 mm laminated inside two 0.25 mm thick sheets of Teflon was placed between the steel cover plate and aluminum or copper plate at the top and bottom.
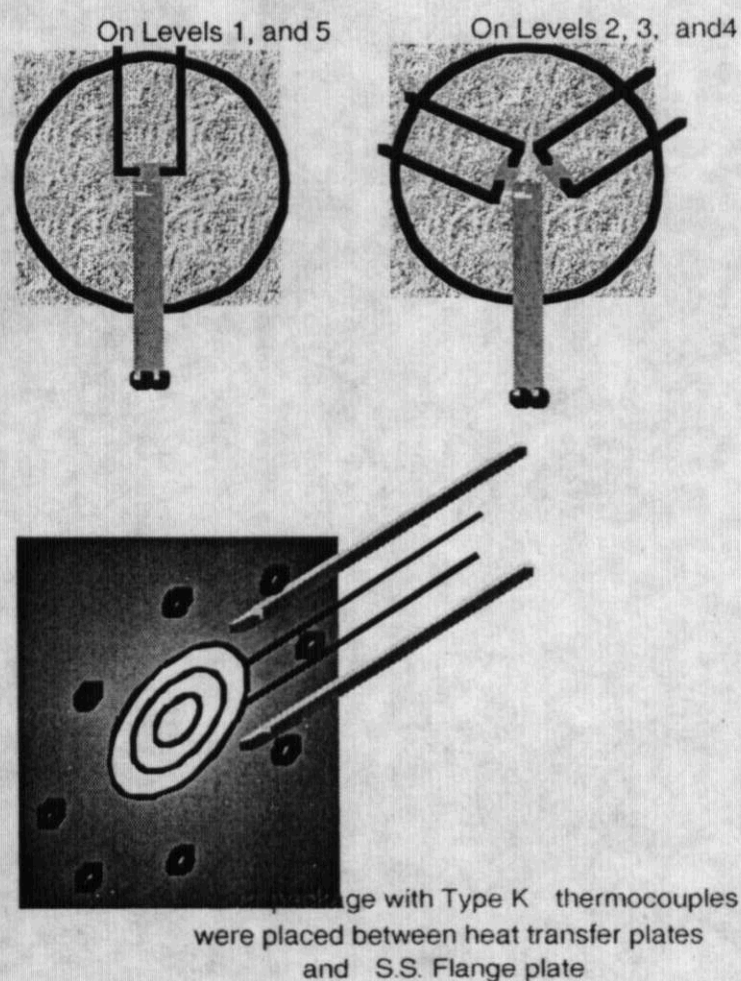
Two type K thermocouples from RDF Corporation are in this heater package to monitor temperature and control the heating rate of the heaters. The temperature measuring system is accurate to ±5 °C. No thermocouples were placed internal to the steel encased PBX 9501 or LX-04 to allow a simple pressure seal designs for this steel fixture. The heater controllers were programmed for the heating rates. A computer using a LABVIEW program collected the thermocouple data every 10 secs.. For all experiments the heat was delivered to the donor at a rate of 5.7 °C a minute until the thermocouples at the heater package recorded 170 ° C. The heaters overshot a few degrees for about 7 minutes and then the temperature came back to 170 ° C for about 30 minutes, then the heating rate in the heater package went to 1° C/min until the explosive thermally reacted.

Acceptor stacked discs with in-situ pressure gauges at various distances from the front impact face were built differently for each explosive cook-off experiment and will be described separately. The carbon resistor gauges were placed in machined grooves in the acceptor disc surfaces which means that the center of this gauge is 0.8 mm from the acceptor disc interface. The manganin gauges and thermocouples were laminated between two 0.13 mm thick Teflon insulating sheets and placed between the acceptors' machined discs. The TEXT IV acceptor was made of Teflon and was in contact with the top steel plate of the donor. It had
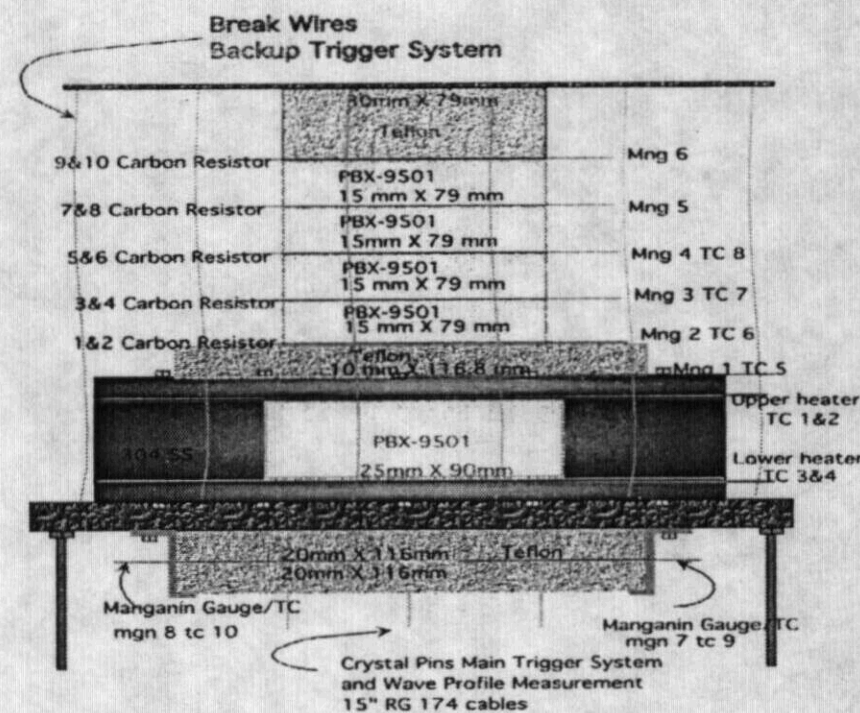
carbon resistor gauges, manganin gauges and type K thermocouples at explosive interfaces placed 19 and 25 mm from the donor's top steel plate. No carbon resistor gauge was placed right at the top steel plate/explosive interface, because this gauge is temperature sensitive. Gauge layouts and heater packages are all similar to that shown for TEXT VI in Figure 1. For TEXT VI the manganin, carbon resistor gauges, and thermocouples were placed at interface depths of 10, 25, 40, 55, and 70 mm in the acceptor. A 10 mm thick Teflon disc is placed between the steel top plate of the confined donor system and the acceptor to provide thermal insulation for the acceptor charge. This insures that the acceptor does not overheat and cook-off. A second benefit is to keep the temperature lower on the carbon resistor gauges since pressure calibration at temperature other than room temperature have not been done. The schematic drawing for TEXT VI is shown in Figure 2.

TEXT VII is shown in Figure 3 with the 79 mm diameter PBX 9501 acceptor placed at a 100 mm standoff from the top steel plate of the donor. The manganin and carbon resistor gauges were placed at the interfaces of the acceptor discs at 0, 8,16, 24,and 32 mm from the 9.3 mm thick steel plate the acceptor was sitting on. This steel plate was 100 mm from the top of the donor's steel top plate.

On Levels 1, and 5   On Levels 2, 3, and 4

...ge with Type K thermocouples were placed between heat transfer plates and S.S. Flange plate

FIGURE 1. TEXT VI GAUGE AND HEATER PACKAGES

FIGURE 2. SCHEMATIC FOR TEXT VI

TEXT VIII is similar to TEXT VI except it has a LX-04 acceptor with manganin, carbon resistor gauges, and thermocouples placed at interfaces at 10, 25, 40, 55, and 70 mm in the 79 mm diameter LX-04 cylinder. A 10 mm thick by 116 mm diameter Teflon disc is placed between the steel top plate of the confined donor system to provide thermal insulation for the acceptor charge and carbon resistor gauges.

TEXT IX acceptor was made of Teflon and was in contact with the top steel plate of the donor. It only had carbon resistor gauges and type K thermocouples at Teflon disc interfaces, placed 20 and 28 mm from the donor's top steel plate. The first acceptor Teflon disc was 116 mm diameter by 20 mm thick, while the second Teflon disc was 79 mm diameter by 8 mm thick.

The triggering of the power supplies and the digitizers is a critical feature of this experiment. For the primary triggering system and to measure the wave arrival times at the bottom steel plate surface, a series of thirteen PZT pins were held in a Teflon disc and placed against the bottom steel plate of all donor assemblies. The pins were in a cross pattern with one pin at the center and each pin being 13.7 mm center to center distance apart. These pins can be seen just below the acceptor in Figure 2 and 3. The thirteen PZT pins were all summed so that any one of them would trigger the digitizers and the power supply for the manganin gauge. A back-up break wire trigger system designed for the STEX cook-off experiments[1] was also used. This system provided a trigger pulse from a circuit if

any of the wires break. These break wires were also summed so the first one would trigger the digitizers and power supplies. The modern Tektronix TDS digitizer continuously records data until a trigger signal stops it. The digitizer then captures events ahead and behind the trigger signal at amounts determined by the chosen settings. This gives some flexibility in performing these cook-off experiments, because there is always uncertainty as to when and where the trigger signal will originate. To measure the time of arrival of the accelerated top steel plate at the acceptor in TEXT VII, another cross pattern of 13 PZT arrival pins was used. Five pins were placed 15 mm in front surface and eight were placed 25 mm in front of the front steel acceptor plate. The placement of these pins within the acceptor can be seen in Figure 3.
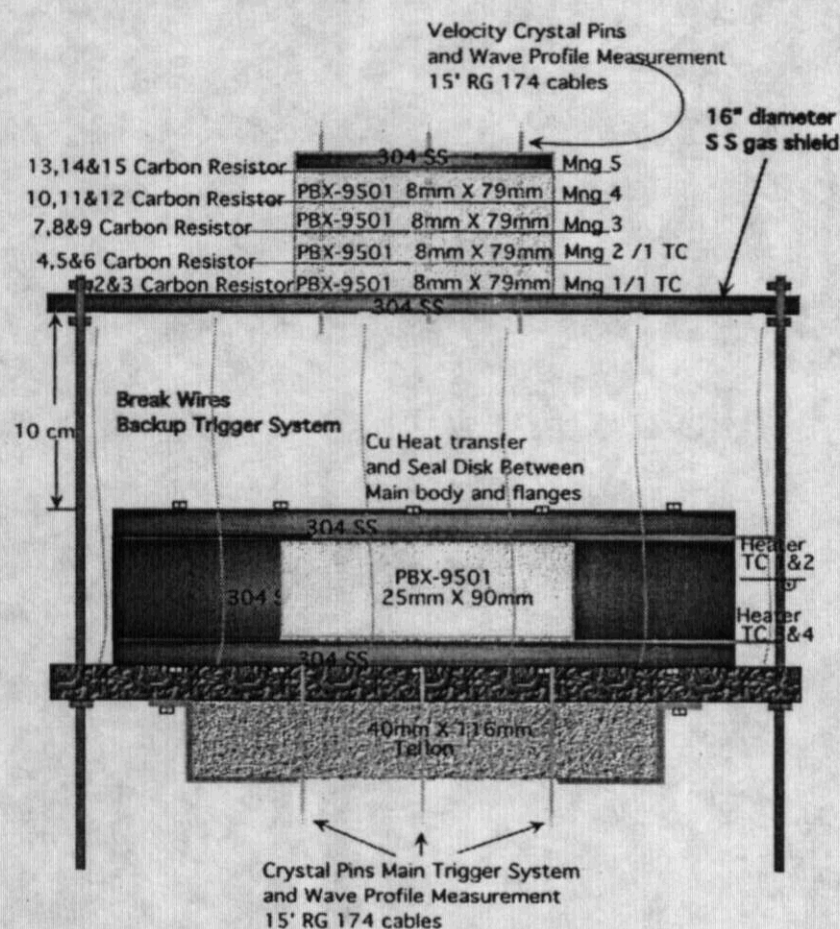

FIGURE 3. SCHEMATIC OF TEXT VII

Carbon resistor and manganin foil gauges require a constant current source to allow direct correlation of the measured voltage change to resistance change. The change in resistance has been calibrated as a function of pressure for both of these gauges at room temperature. The constant current allows conversion of measured voltage signals directly to pressure. The constant current power supply for the carbon resistor gauges is always turned on sending 18 mA through the 470 Ω resistors. The constant current pulse for the manganin gauges was provided by a Dynasen CK2-50/0.050-300 power supply that gave the gauge a constant current of 30-50 A.

RESULTS

Table 1 gives a general summary of results for these experiments. A high-pressure ramp wave was measured in TEXT IV by carbon resistor gauges with peak pressure near 0.43 GPa at a depth of 19 mm and 0.35 GPa at a depth of 25 mm into the Teflon acceptor. The carbon resistor gauges appear to have broken just after reaching peak pressures. The analysis of pin arrival times with their location for TEXT IV indicates that the reaction started slightly off center. The phase velocity across the steel surface where the PZT pins were located gave a velocity of about 1 mm/μs. This subsonic phase velocity shows that a deflagration occurred and not a true constant volume thermal explosion. The measured pressure pulses are also consistent with this being a deflagration wave.

The carbon resistor pressure gauge results (without temperature corrections) for TEXT VI are shown in Figure 4. A ramp wave with peak pressure of 1.2 GPa exists at the first gauge level in the acceptor. Some variation in gauge pressure exists for gauges on the same plane, which is likely due to the ramp wave not being symmetric as it propagates into the acceptor. The ramp pressure wave decays very rapidly as it moves up the acceptor charge and the rise time of the ramp lengthens. This decay is faster than observed in the Teflon acceptor of TEXT IV consistent with PBX 9501 being a stiffer material with faster release wave speeds. It is clear from the gauge records that the wave did not build toward violent reaction or detonation, which would be a much more severe safety issue. In fact, the peak pressures decay exponentially.

Figure 5 gives the temperature time profiles for the five thermocouples that behaved well for TEXT VI. Their locations are given in Figure 2. These show that rapid explosion occurred when the thermocouples at the heater package of the donor system reached 209°C. The initial heating rate was 5.7 °C per minute up to 170 °C at the metal surface of the donor. Then the temperature at this surface was held at 170 °C for 35 minutes to allow for the donor to be somewhat uniform in temperature. The temperatures in the acceptor did increase but at much lower magnitude and rate. However, these acceptor temperatures are high enough that calibration of the carbon

TABLE 1. GENERAL SUMMARY OF EXPERIMENTS

| Shot number	Donor material	Acceptor	Heater package Temperature at Ignition (°C)	Results
TEXT IV	295 g PBX 9501 with initial density of 1.82 g/cc	Teflon cylinder in contact with donor assembly	208	Pressure ramp of 0.4 GPa peak with 100's μs rise time
TEXT V	Teflon	Teflon	N/A	Profile of temperature inside Teflon donor
TEXT VI	295 g PBX 9501 with initial density of 1.82 g/cc	PBX 9501 cylinder n contact with donor assembly	209	Pressure ramp of 1.2 GPa peak with 100's μs rise time
TEXT VII	295 g PBX 9501 with initial density of 1.82 g/cc	PBX 9501 cylinder stood off by 100 mm	208	Pressure ramp wave with peak 1.0 GPa with 100's μs rise time from a warped plate impact traveling at 0.55 mm/μs
TEXT VIII	301 g LX-04 with initial density 1.86 g/cc	LX-04 cylinder in contact with donor assembly	220	No measurable pressure wave from very non-violent reaction
TEXT IX	176 g LX-04 (loose packed to density of 1.05 g/cc)	Teflon cylinder in contact with donor assembly	220	Minor reaction?

resistor gauge for these temperatures is needed to improve the accuracy of these measurements. Note that TEXT V measured the temperature inside a Teflon donor assembly with thermocouples at various depths using the same heating rates as used in the explosive experiments so thermal histories of explosive donors can be calculated in future work.

The heating history provided by the thermocouple outputs for TEXT VII went to 170 °C at a rate of 5.7 °C a minute. The controllers then allowed the heaters to overshoot to 175°C for 7 minutes and then brought the temperature back to 170 °C for 30 minutes. The heating rate at the heater package then went to 1°C/min until the temperature at the steel plate reached 210°C and the PBX 9501 donor exploded. Thermocouples 5 & 6 were located at the interface between the acceptor's steel plate and the first PBX 9501 disc. The thermocouples in the acceptor showed only a few degrees

temperature rise during this experiment as was expected.

The data from the trigger and arrival time pins at the bottom of TEXT VII donor assembly indicates that a reaction pressure wave started near the center of the charge and the wave swept out from the center across the bottom steel plate. The pins near the center reported a rapid phase velocity of near 1.8 mm/μs, while the velocity from the center to outer pins registered phase velocities near 1 mm/μs. This suggests that the reaction that bulged the center closing the center pins. The reaction then spread radially outward from the center to outer pins registered phase velocities near 1 mm/μs. This suggests that the pushing the plate section just above the reaction front into the pins.

Figure 6 gives the measured contours of the flying top donor steel plate just before impacting the steel plate that the acceptor was sitting on.
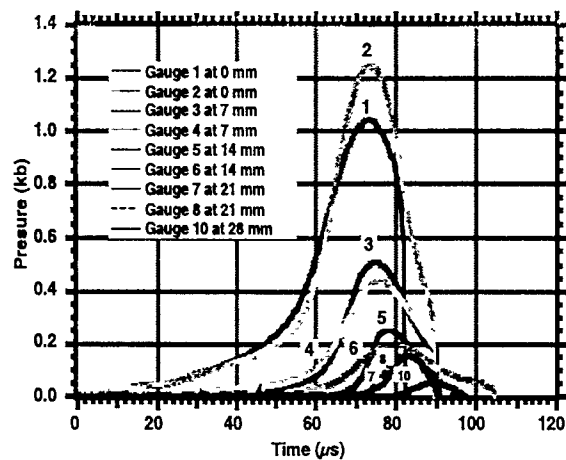
A.
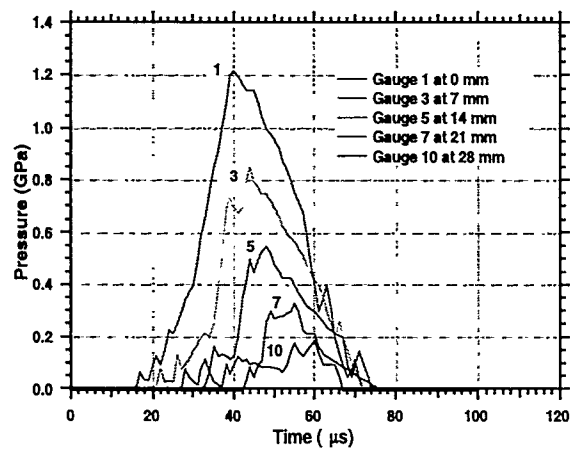
B.

FIGURE 4. EXPERIMENTAL (A) AND CALCULATED (B) PRESSURE RESULTS FOR TEXT VI

These contours were determined from the plate's velocity and arrival times at the array of pins ahead of the acceptor. The plate is traveling at an average velocity of 0.55 ± 0.04 mm/µs. Based on the limited pin data, the flying plate had a oblate spheroid shape (i.e. shape of the back of a door knob).
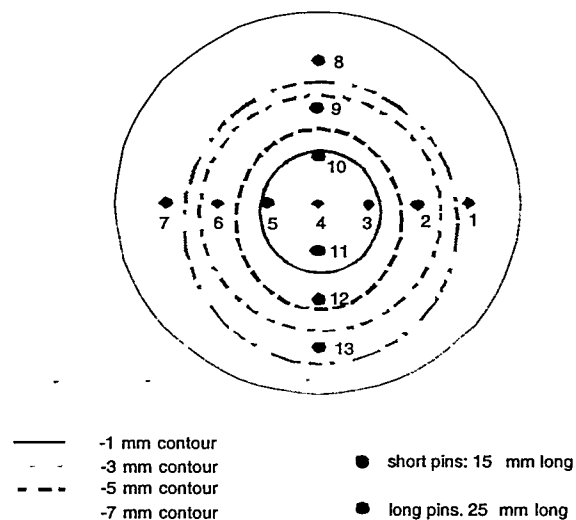
The carbon resistor gauge records for TEXT VII are given in Figure 7. The ramp wave's peak pressure decays rapidly as the wave travels through the acceptor. The pressure wave has a peak of 1.0 GPa at the first PBX 9501 acceptor disc decreasing to 0.4 GPa after a 32 mm run distance into the PBX 9501acceptor. The ramp wave in these records with structure later in time is due to the three-dimensional loading of the warped flyer plate. This pressure

amplitude did not cause significant reaction in the PBX 9501 acceptor charge.

The results for TEXT VIII are very qualitative since no pressure wave was measured. A standard video (60 Hz) of the event showed the bolts broke at 220 °C causing the assembly to become airborne a few inches which pushed the acceptor aside. The donor had flames coming from one side of it. The acceptor was recovered intact with gauges still functional.
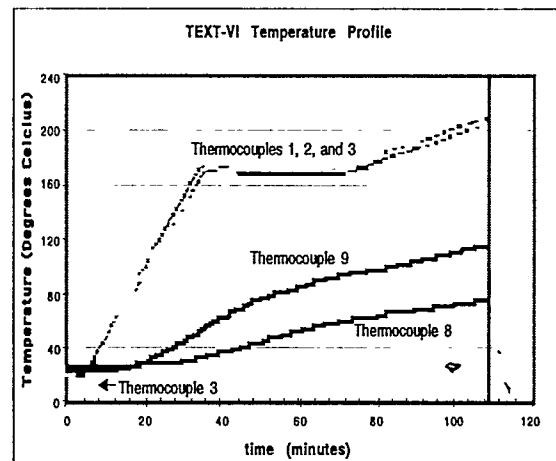
FIGURE 5. TEMPERATURE PROFILES OF VARIOUS THERMOCOUPLES AT VARIOUS LOCATIONS IN THE TEXT VI TARGET

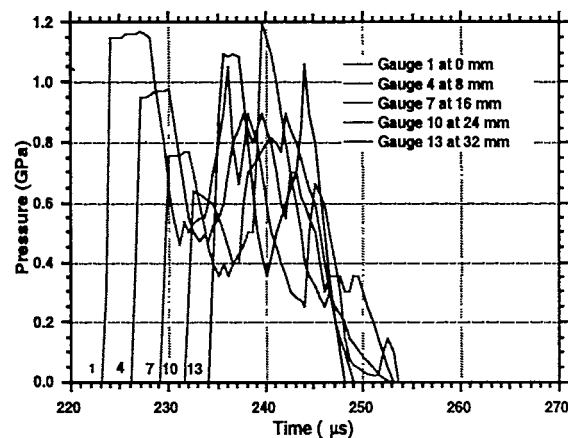|		
———	-1 mm contour	
- -	-3 mm contour	● short pins: 15 mm long
▬ ▬ ▬	-5 mm contour	
	-7 mm contour	● long pins. 25 mm long

FIGURE 6. TEXT VII FLYER PLATE CONTOUR AS MEASURED BY ARRIVAL PINS IN FRONT OF ACCEPTOR
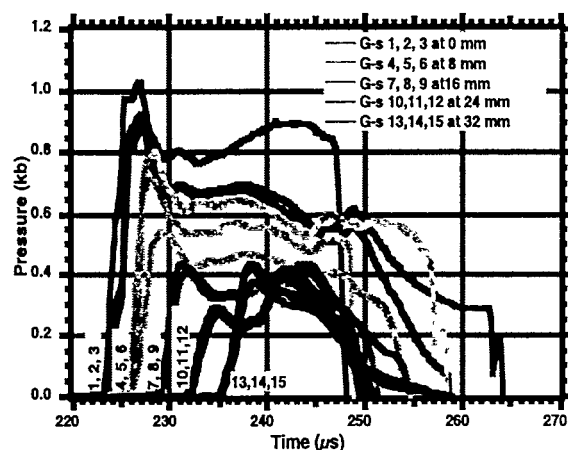
A.

B.

FIGURE 7. MEASURED (A) AND CALCULATED (B) PRESSURES FOR TEXT VII EXPERIMENT.

REACTIVE FLOW MODELING OF THESE EXPERIMENTS

The experimental geometry of TEXT VI was modeled in the DYNA2D hydrodynamic computer code. Initially, the PBX 9501 donor charge was detonated which showed that the observed pressure profiles in the PPBX 9501 acceptors were far too low to have been caused by a detonation wave. This was also found to be true for a constant volume explosion of the entire donor charge. To realistically model TEXT VII, the PBX 9501 was assumed to deflagrate at approximately 500 m/s from its bottom surface toward the steel plate to be accelerated into the PBX 9501 acceptor using the DYNABURN

option of the code. DYNABURN is an outgrowth of the widely used Ignition and Growth reactive flow model for shock initiation and detonation wave propagation in solid explosives.[14] A small initial pressure initializes DYNABURN and/or fraction reacted in the elements where the reaction is known or assumed to begin. A subsonic deflagration wave is then propagated using the pressure and particle geometry dependent growth of reaction terms of the Ignition and Growth model. This reactive flow option has been used to model air bag propellants, internal ballistics of guns, explosive and propellant deflagration, and other violence of thermal explosion experiments.[15]

In the TEXT VI calculations, a pressure ramp wave is transmitted to the in-contact PBX 9501 acceptor. The peak magnitude and rise-times of these pressure ramp waves are similar to the experimental measurements. The calculated decay of the peak pressure as the ramp wave moves deeper into the PBX 9501 acceptor is in good agreement. Figure 4 shows the calculated pressure histories in the PBX 9501 acceptor at the embedded gauge depths. The calculated peak pressures agree well with those measured with carbon resistor gauges. Since a simple elastic-plastic model was used for PBX 9501, the calculated compression times are shorter than those observed experimentally and the measured early low pressure ramp was not calculated. The calculated pressure histories are decaying rapidly as they propagate through the PBX 9501 and do not evolve into shock waves that could cause any significant reaction.

The same modeling approach was used for the PBX 9501 cook-off for TEXT VII. In this case, the hyrodynamic code calculated the donor's top steel plate accelerating across the stand-off distance following the deflagration process. The calculations showed that the donor's top steel plate reached its terminal velocity of 0.51 mm/μs in less than the 100 mm experimental stand-off distance. This calculated velocity is within the uncertainty in the experimental measurement, 0.55 +/- 0.04 mm/μs. Figure 7 shows the resulting calculated pressure histories in the PBX 9501 acceptor charge at the 0, 8, 16, 24, and 32 mm depths where the carbon resistor gauges were located. The calculated pressures and rise times are in better agreement with the steeper shocks created by the flyer plate impact with PBX 9501 in TEXT VII than the

7

ramp waves created in the in-contact experiment TEXT VI. The Ignition & Growth PBX 9501 reactive flow model normalized to LLNL and LANL embedded gauge records for shock initiation[17] predicts that these pressure waves do not cause significant reaction, and no buildup to violent reaction is predicted.

The general agreement between these calculated records and the carbon gauge records in Figures 4 and 7 show that these resistor gauges are recording the peak pressures and pulse durations with accuracy better than 20%. The attenuation of the peak pressures are faster in the experiments than in the calculations, and the pressure releases in the calculations is faster than in the gauge records. Further experimentation and more sophisticated reactive flow modeling are required to address these differences. Part of the difference is likely due the carbon resistor gauges hysteresis upon release of pressure.

No significant pressure was calculated from the cook-off of the LX-04 donor in TEXT VIII. The calculated time to thermal explosion in TEXT VIII using the LX-04 multistep chemical kinetic decomposition model of Tarver and Tran[16] was 7677 seconds, in good agreement with the experimental time of 7380 seconds considering that the temperature measuring system has an uncertainty of 5 °C and the thermocouples were not embedded in the LX-04 donor.

LX-04 has never exhibited the rapid deflagration wave velocities of several hundred meters per second (often called deconsolidated burning) that HMX-based explosives containing over 90% HMX have demonstrated in the strand burner[18], diamond anvil cell[19], and simulated crack experiments.[20] LX-04 deflagration velocities of less than 100 m/s resulted in no significant pressures being delivered to the acceptor charge in TEXT VIII and TEXT IX simulations. If the deflagration velocity of LX-04 remained relatively slow (tens of meters per second or less) following thermal explosion, then it is not surprising that these and previous LX-04 thermal explosions[1,15] were not violent and no measurable pressures were generated in the TEXT VIII and TEXT IX acceptors.

SUMMARY AND CONCLUSIONS

Carbon resistor pressure gauges have been used successfully in two-dimensional shock wave experiments where time resolution and accuracy were sacrificed for survival of the gauge. The carbon resistor pressure gauge results (without temperature corrections) for the experiments using PBX 9501 donors show a ramp wave with peak pressures of 1 GPa magnitude and rise times of 100's of microseconds. The ramp pressure wave decays very rapidly as it moves through the acceptor charge and the rise time of the ramp shortens. The ramp wave in the acceptors did not build into a detonation for any experiment.

In TEXT VI, the pressure ramp wave is transmitted to the in-contact PBX 9501 acceptor. The calculated peak magnitude and rise-times of these pressure ramp waves are in good agreement with the experimental measurements. The calculated decay of the peak pressure is also in good agreement.

In TEXT VII the gauged PBX 9501 acceptor was at a standoff distance of 100 mm from the donor's steel cover plate. A multi-dimensional ramp pressure wave was transmitted to the PBX 9501 acceptor from the impact of the curved steel plate accelerated over the 100 mm stand-off distance by the thermal explosion of a confined PBX 9501 donor system. The peak pressure in the PBX 9501 acceptor was 1.0 GPa decreasing to 0.4 GPa at a 32 mm run distance. The ramp wave showed extra features compared to the other experiments. It is believed that this extra structure is due to the three-dimensional loading from the tilted and curved flyer plate's impact. The measured pressures are strong enough to scatter burning materials around, but will not build-up to detonation in the accepter under these experimental conditions. The DYNA2D modeling of this experiment gives results which are in good agreement with the experiment.

The Ignition and Growth reactive flow model for the shock initiation of PBX 9501, which has been normalized to a great deal of experimental data from LANL[17], predicts no significant exothermic reaction in this PBX 9501 acceptor charge. Therefore, the model results imply that

no shock initiation and subsequent buildup to detonation will occur from this type of thermal explosion test. This is consistent with the results of other thermal explosion experiments on HMX-based PBX's containing 85 - 95% HMX.[1,15]

In TEXT VIII no pressure waves were measured in the acceptor when the donor reacted. In fact, the acceptor was recovered intact with useable gauges. Flame was observed from the donor. This mild reaction result for LX-04 is consistent with STYX test results[1] where the heating rate was 1 °C/hr.

Future work in this area will include additional experiments with different heating rates, material porosity and confinement. Calibration of carbon resistor gauges at temperatures to 100 °C will be done. The thermal and hydrodynamic coupled code ALE3D will be used to model these and future experiments.

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